Relic neutralinos and the two dark matter candidate events of the CDMS II experiment

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(Received 23 December 2009; published 14 May 2010)

The CDMS Collaboration has presented its results for the final exposure of the CDMS II experiment and reports that two candidate events for dark matter would survive after application of the various discrimination and subtraction procedures inherent in their analysis. We show that a population of relic neutralinos, which was already proved to fit the DAMA/LIBRA data on the annual-modulation effect, could naturally also explain the two candidate CDMS II events, if these are actually due to a dark matter signal.

DOI: 10.1103/PhysRevD.81.107302 PACS numbers: 95.35.+d, 12.60.Jv

The search for a sign from dark matter (DM) involves direct detection, consisting in the measurement of the effects induced by the feeble interaction of the DM particles with the material of a low-background setup, and indirect measurements. These concern many possible signals, ranging from neutrinos to charged cosmic rays (positrons, antiprotons, antideuterons), to gamma rays, to a radio signal, and even to effects induced on the cosmic microwave background.

In Ref. [1] we have shown that the annual-modulation effect at an 8.2σ C.L., obtained by the DAMA/NaI and DAMA/LIBRA experiments (with a total exposure of 0.82 ton yr) [2], is very well fitted by relic neutralinos in an effective minimal supersymmetric standard model (effMSSM) at the electroweak scale defined in terms of a limited number of parameters. We recall that the effect measured by the DAMA Collaboration is the first and up-to-now unique evidence for a signal compatible with a typical signature (annual modulation) expected for dark matter particles [3].

Other experiments of weakly interacting massive particle (WIMP) direct detection do not currently have the capability of measuring the annual-modulation effect and usually provide upper bounds for the expected signals [4]. These limits are obtained through complex procedures for discriminating electromagnetic signals from recoil events and through delicate subtractions meant to separate putative WIMP signals from neutron-induced events. A major critical point in these experiments and related analyses is that the very signature (the annual modulation) of the searched signal cannot be employed in extracting the authentic events. Other potential difficulties are related to stability features and determination of the threshold and of the energy scale.

In Ref. [1] it was also pointed out that the inclusion of these upper bounds, taken at their face value, would anyhow allow a compatibility with the DAMA data for a range in the WIMP (neutralino) mass around 7–10 GeV. A similar result has also been obtained in Ref. [5].

The CDMS Collaboration has presented its results for the final exposure of the CDMS II experiment [6]. In that paper it is reported that two candidate events for DM would survive after application of various discrimination and subtraction procedures, though there is a probability of 23% that they are of a more prosaic origin. These two events have recoil energies of 12.3 keV and 15.5 keV.

If one assumes that the two candidate events are due to a WIMP particle with a coherent interaction with nuclei, taking into account the CDMS total exposure, one can derive that the relevant 90% C.L. region in the plane m_χ-$\xi\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}}$ (up to a WIMP mass of 100 GeV) is the one displayed in Fig. 1 [m_χ denotes the WIMP mass, $\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}}$ is the WIMP-nucleon coherent cross section, and ξ is the WIMP local fractional density). In this figure, due to the low statistics, we have adopted the simple criterion of requiring $n = 2$ WIMP events ($0.6 < n < 4.7$ at 90% C.L. for a Poissonian distribution) in the total range of the recoil energy E_R observed by CDMS, $10\ \mathrm{keV} < E_R < 100\ \mathrm{keV}$. This is sufficient to capture the main features of the allowed region. This is also true for $m_\chi \lesssim$ 8.5–9 GeV where, depending on the values of the escape velocity in the Galaxy and on the rotational velocity of the Solar System, the event with $E_R = 15.5$ keV could not, in principle, be ascribed to a WIMP. In fact, in this case the region shown in Fig. 1 overlaps with the one (not shown in Fig. 1) obtained by requiring only one WIMP event ($0.11 < n < 3.44$ at 90% C.L.) for $10\ \mathrm{keV} < E_R < 12.3$ keV: the region obtained with this criterion has an upper boundary about 25% smaller than the one shown in Fig. 1, and the lower boundary is reduced by about a factor of 5.

In Fig. 1 the annual-modulation regions of the DAMA Collaboration are also shown, with and without inclusion of the channeling effect [7]. The exact modeling of channeling is still under study; one therefore expects that the actual physical situation is comprised within the two regions represented in the figure. As a reference model for

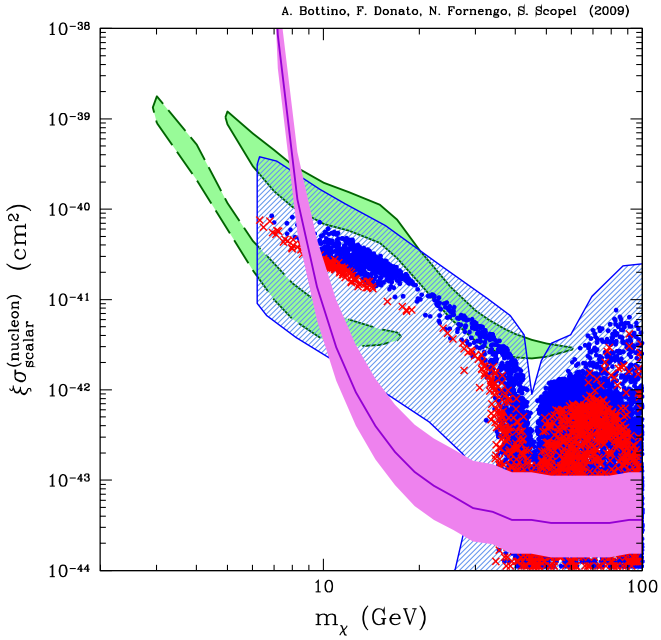

FIG. 1 (color online). $\xi\sigma_{\rm scalar}^{\rm (nucleon)}$ as a function of the WIMP mass. The (green) shaded regions denote the DAMA/LIBRA [2] annual-modulation regions, under the hypothesis that the effect is due to a WIMP with a coherent interaction with nuclei; the region delimitated by the solid line refers to the case where the channeling effect is not included, and the one with a dashed contour to the case where the channeling effect is included [1]. The (violet) band displays the region related to the two CDMS candidate events, obtained from the total rate in the whole energy window. The scatter plot represents supersymmetric configurations calculated with the model summarized in the Appendix, at a fixed representative set of values for the hadronic quantities. The (red) crosses denote configurations with a neutralino relic abundance which matches the Wilkinson Microwave Anisotropy Probe cold dark matter amount ($0.098 \leq \Omega_\chi h^2 \leq 0.122$), while the (blue) dots refer to configurations where the neutralino is subdominant ($\Omega_\chi h^2 < 0.098$). The region covered by a (blue) slant hatching denotes the extension of the scatter plot upwards and downwards, when the hadronic uncertainties in the scattering coherent cross section are included.

the WIMP halo distribution, a cored-isothermal sphere is employed with the following parameters: local value of the rotational velocity $v_0 = 220\ \mathrm{km\,s^{-1}}$, escape velocity $v_{\rm esc} = 650\ \mathrm{km\,s^{-1}}$, and total nonbaryonic dark matter density $\rho_0 = 0.34\ \mathrm{GeV\,cm^{-1}}$. Obviously, the DM halo distribution could be quite different [8]: this would induce a shift of the actual position of the regions and bounds, as discussed and shown e.g. in Ref. [1].

In Fig. 1 we also display the scatter plot representing the supersymmetric configurations calculated within a realization of the minimal supersymmetric standard model where gaugino unification is relaxed [1,9]. For convenience, the model is summarized in the Appendix. The scatter plot refers to a fixed representative set of values for the hadronic quantities involved in the neutralino-nucleon cross sections [1]. The region covered by a (blue) slant hatching denotes the extension of the scatter plot upwards and downwards, when the hadronic uncertainties extensively discussed in Ref. [1] are included.

From Fig. 1 and the previous discussion about the CDMS region, one finds that the putative CDMS events are simultaneously compatible with the DAMA/LIBRA data and the theoretical evaluations in the mass range 8–12 GeV. It is worthwhile to point out that at such low masses the expected recoil spectrum depends on the high velocity tail of the velocity distribution, which is sensitive to the details of the astrophysical model and, in particular, to the escape velocity. Other possibilities for the modeling of the velocity distribution have been discussed in [8]. We also stress that the explanation—in terms of the relic neutralinos in the supersymmetric model discussed here—of the annual-modulation data alone extends over a much wider range; for instance, for the case of a WIMP halo distribution given by a cored-isothermal sphere with the parameters mentioned above, this extended range can be simply read from Fig. 1 to be $6\ \mathrm{GeV} \lesssim m_\chi \lesssim 60\ \mathrm{GeV}$. These light neutralinos can also be complementarily investigated by indirect means, such as cosmic antiprotons [1,10] and antideuterons [1,11] and signals at neutrino telescopes [12], and, most notably, they can be searched for at the Large Hadron Collider [13]. Astrophysical bounds arising from multiwavelength analyses [14], which may be strong depending on assumptions on the DM distribution and on astrophysical properties, like those related to cosmic-ray propagation and energy losses, do not markedly constrain the supersymmetric configurations of Fig. 1, especially when astrophysical uncertainties are properly taken into account.

Our previous analysis was based only on the total rate taken over the whole recoil energy range observed by CDMS II, without using any spectral information. This is motivated by the very low statistics (two events), which makes a statistical analysis of the energy spectrum very critical (and to some extent not fully justified). However, forcing the situation somewhat, one can wonder what would produce an analysis in terms of the energy spectrum. In Figs. 2 and 3 we therefore show the regions compatible with the two CDMS II events at 12.3 keV and 15.5 keV, taking into account the spectral behavior of the theoretical recoil rate. In the determination of the allowed regions we have adopted a maximal likelihood analysis [15]. Figure 2 shows the case of a negligible background contribution, and the contours refer to confidence levels of 68%, 90%, and 95%, from the innermost to the outermost. Figure 3 instead refers to the presence of a background contribution, which we have modeled as in Ref. [16], i.e. with an energy dependence $dN/dE = -0.002\,95 + 0.463/E$ normalized to a total number of events equal to 0.8, to conform to an estimate of the background contribution of $0.8 \pm 0.1(\mathrm{stat}) \pm 0.2(\mathrm{syst})$ [6]. In the case of Fig. 3, the contours

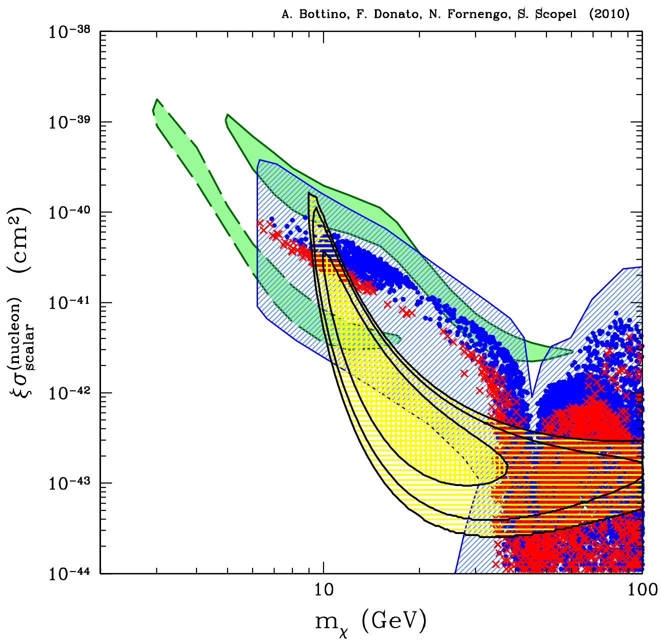

FIG. 2 (color online). The same as in Fig. 1, except that the (yellow) shaded regions compatible with the CDMS II candidate events are obtained by a maximal likelihood method applied to the differential energy recoil rate, under the hypothesis of negligible background. The contours refer to (from the internal to the external one) 68%, 90%, and 95% C.L.

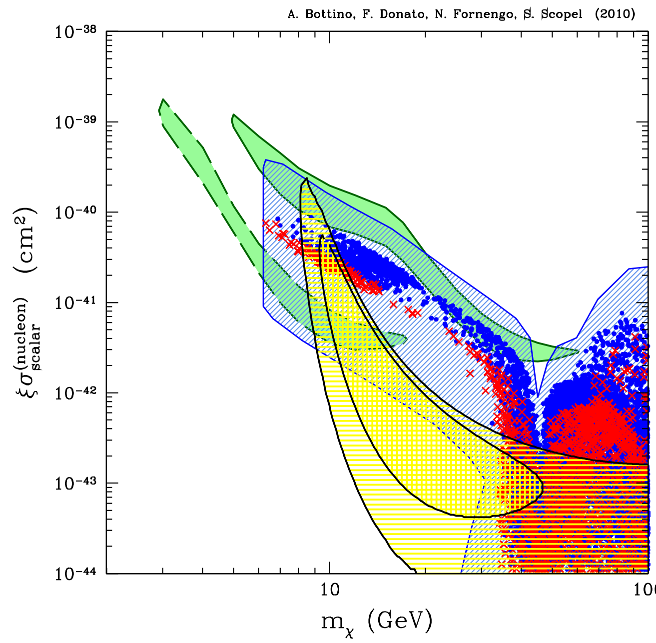

FIG. 3 (color online). The same as in Fig. 2, but under the hypothesis of a background contribution as in Ref. [16], normalized to 0.8 events in the whole energy window of CDMS II. The contours refer to (from the internal to the external one) 68% and 85% C.L.

refer to 68% and 85% C.L., and they evolve into an open region (i.e. into an upper bound) at the 90% C.L., a result compatible to the one obtained in Ref. [16], where a slightly different statistical analysis was adopted. Figures 2 and 3 are quite compatible with the results of Fig. 1 obtained by using the total counting number, and they reinforce our conclusions about compatibility between DAMA and CDMS II for light WIMPs, and between these experimental results and our supersymmetric models with light neutralino dark matter.

In conclusion, in this paper we have considered the two events which, in the analysis of CDMS II, seem to survive after the various discrimination and subtraction procedures. We have shown that, should these events be due to WIMP-nucleus coherent interactions, this result would be compatible both with the annual-modulation signal previously reported by the DAMA Collaboration and with an interpretation in terms of relic light neutralinos. This conclusion is not affected by other upper bounds of direct dark matter detection. In particular, the XENON upper bound [17] suffers from large uncertainties due to conflicting determinations of the scintillation efficiency at low nuclear recoils (as shown in Fig. 12 of [18]). Calculations performed in Ref. [18] (though with a threshold energy somewhat smaller than the one of XENON10) indicate that at a WIMP mass of order 10 GeV, the bound of Ref. [17] should be relaxed by more than an order of magnitude. One should furthermore note that in XENON10 the energy scale is particularly uncertain due to a calibration at an energy much higher than the declared threshold energy.

Work supported by research grants funded jointly by Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR, under Contract No. 2008NR3EBK), by Università di Torino, by Università di Padova, and by the Istituto Nazionale di Fisica Nucleare (INFN) within the *Astroparticle Physics Project*. S. S. is supported by the WCU program (R32-2008-000-10155-0) of the National Research Foundation of Korea. N. F. acknowledges support from the Spanish MICINN ConsoliderIngenio 2010 Programme under MULTIDARK Grant No. CSD2009-00064.

Note added.—After submission of the present paper, the CoGeNT Collaboration [19] presented the results of a search for light-mass DM particles, where an irreducible excess of bulklike events below an energy of 3 keV is observed. As discussed in Ref. [19], if this population of five events were due to WIMP interactions with the detector, they would entail a WIMP mass of 7–12 GeV with a cross section m_χ-$\xi\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}} \simeq (3\text{–}10) \times 10^{-41}$ cm^2, thus in a region in agreement with predictions of our model, with the DAMA/LIBRA and CDMS II results.

APPENDIX: THE SUPERSYMMETRIC MODEL

The supersymmetric scheme we employ in the present paper is the one described in Ref. [1] as an effMSSM at the electroweak scale, with the following independent parameters: M_1, M_2, M_3, μ, $\tan\beta$, m_A, $m_{\tilde{q}}$, $m_{\tilde{l}}$, and A. Notations are as follows: M_1, M_2, and M_3 are the U(1), SU(2), and SU(3) gaugino masses (these parameters are taken here to be positive), μ is the Higgs mixing mass parameter, $\tan\beta$ is the ratio of the two Higgs vacuum expectation values, m_A is the mass of the CP-odd neutral Higgs boson, $m_{\tilde{q}}$ is a squark soft mass common to all squarks, $m_{\tilde{l}}$ is a slepton soft mass common to all sleptons, and A is a common dimensionless trilinear parameter for the third family, $A_{\tilde{b}} = A_{\tilde{t}} \equiv A m_{\tilde{q}}$ and $A_{\tilde{\tau}} \equiv A m_{\tilde{l}}$ (the trilinear parameters for the other families being set equal to zero). In this model no gaugino mass unification at a grand unified scale is assumed, whence light neutralinos arise.

The parameter space of this model is bounded by a large host of experimental data: invisible Z decay (for decay into light neutralinos), direct searches of supersymmetric particles and Higgs bosons at the CERN LEP and Fermilab Tevatron, supersymmetric contributions to rare processes [$\mathrm{BR}(b \to s + \gamma)$, $\mathrm{BR}(B_s^0 \to \mu^- + \mu^+)$], and measurements of the muon anomalous magnetic moment $a_\mu \equiv (g_\mu - 2)/2$. Other details about the model and the relevant constraints can be found in Ref. [1].

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